Incorporation of life cycle emissions and carbon price uncertainty into the supply chain network management of PVC production

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Abstract

Emissions trading schemes have been widely implemented by many countries to enforce the “cap and trade” concept for mitigating CO_2 emissions. Thus, the carbon price influences the manufacturing costs in all stages of production, recycling, and disposal. Consideration of the carbon price is especially important for the economic efficiency of the downstream manufacturing sectors, such as in plastic product manufacturing, to substantially reduce their costs through the design and management of networked supply chains, which results in purchasing feedstocks from different technological routes, as well as choosing plants, warehouses and various transportation modes with diverse CO_2 emission intensities. Supporting the decision-making in such situations requires the integration of life cycle analysis and networked supply chain management methodologies with an analysis of the carbon-market uncertainties. Such approaches have not been sufficiently quantified in the existing literature. This study presents a stochastic mixed-integer linear programming model developed for polyvinyl chloride (PVC) pipe manufacturing in China, which is used to evaluate the effects of the life cycle emissions of procurement on the whole supply chain under carbon market uncertainty. Our results illustrate that the carbon market uncertainty would not only significantly influence the carbon-intensive production sectors but also the downstream manufacturing sectors. The five scenarios with carbon price variation exhibit distinctively different choices in procurement and supply chain configurations, as well as in their performances regarding total emissions and associated costs.

Keywords

Green supply chain management; emissions trading scheme; life cycle analysis; carbon price uncertainty; PVC production

1. Introduction

Environmental and climate change issues play an increasing role in the decision-making processes of supply chain management (SCM) (Sarkis et al., 2011; Zhu and Geng, 2013). The concept of green supply chain design addresses these issues by integrating the environmental and climatic aspects with the traditional economic considerations (Fahimnia et al., 2015). Among the corresponding policies, the emissions trading market provides enterprises with flexibility in achieving emissions reduction and thus impacts carbon-intensive industries such as fossil fuel generation, petro-chemical production and iron and steel manufacturing.

From a life cycle perspective, the uncertainty of carbon prices especially impacts the downstream manufacturing sectors that purchase carbon-intensive feedstocks from various suppliers. The corresponding indirect effects on the whole supply chain have not been sufficiently evaluated in the existing literature. For example, polyvinyl chloride (PVC) in China is mainly produced with coal-based technologies, which have carbon emissions that are roughly three times higher than those of oil-based technologies. Our calculation shows that China's PVC industry emitted 123.54 million tons of CO_2 in 2017, three quarters of which was from coal-based technologies. As China is establishing a nation-wide CO_2 emissions trading system that is expected to gradually include all the industrial sectors, the downstream PVC pipe producers will probably replace the coal-based PVC with the oil-based PVC, which is less carbon-intensive. This procurement alteration may reduce the corresponding upstream emissions by up to 30.89 million tons, provided that the carbon price is sufficiently high. The Life cycle analysis (LCA) is an effective methodology for the comprehensive assessment of the environmental impacts associated with all the production stages, from raw material extraction to disposal or recycling, throughout the entire lifetime of products (ISO, 2006). Integrating LCA into the supply chain network design (SCND) is becoming an important subject of intense academic research. The focus of previous studies varied from environmental and social objectives to methods of integrating the objectives into models to the coverage of industrial applications and contexts (Eskandarpour et al., 2015).

From the perspective of the economic costs, the downstream producers are not affected by the life cycle environmental impacts of the upstream suppliers if the carbon prices are equal to zero. However, when an emissions trading system is established and the price signal is sufficiently high, the downstream producers are exposed to carbon price uncertainty even when their own production processes are not carbon-intensive. The economic efficiency of the downstream manufacturers of chemical products in China can be substantially improved by the above characterized approaches because its corresponding upstream manufacturing can be traced back to the original extraction of various resources, such as coal, crude oil, natural gas and even biomass. Moreover, each product from the chemical industry may be associated with different energy consumption patterns and carbon emissions, as well as other environmental impacts. Thus, the decisions in networked supply chain management are key to the resulting efficiency. However, the downstream manufacturing sectors are subject to large carbon price uncertainty even if their own production processes emit much less CO_2 than the upstream sectors.

Building on the above observations, this study attempts to integrate the LCA with SCM modeling by accounting for the carbon price uncertainty. To do so, a stochastic mixed integer linear programming (MILP) model is first proposed to design and plan a supply chain that is exposed to uncertain carbon prices. Second, as an illustration of the methodological framework, a PVC pipe manufacturing industry in China is used as a case study of networked supply chain management, which produces different kinds of pipes to fulfill the given demand.

The remainder of the paper is organized as follows. Section 2 summarizes the relevant research. Section 3 describes the problem consisting of the whole supply chain, the life cycle analyses of different PVC production approaches, and their integration into the modeling framework. Section 4 defines the model variables, parameters and equations. Section 5 presents the results of the case study analysis. Finally, this study is concluded in some remarks in Section 6.

2. Literature review

2.1 Green supply chain management and LCA

The incorporation of environmental and climate change impacts the SCND decision-making processes in researching the concept of green (or sustainable) supply chain management. Zakeri et al. (2015) compared the performance of a proposed supply chain under two different carbon pricing schemes, namely, carbon tax and carbon emissions trading. Their results favored the latter scheme in terms of emissions generation, costs, and service level schemes. Allevi et al. (2018) evaluated the effects of the application of environmental policies in a multitier closed-loop supply chain network wherein the raw material suppliers, manufacturers, consumers, and recovery centers operate. As a measurement of the environmental impacts throughout the entire supply chain for a certain product, the LCA has received much attention in the field of SCND. Genovese et al. (2017) compared the performance of traditional and circular production systems across a range of indicators, including the direct, indirect and total lifecycle emissions, waste recovered, virgin resources used, and carbon maps. Chaabane et al. (2012) developed a supply chain design model with reverse logistics using an LCA approach to address the emissions trading concerns. Many of these studies assumed deterministic parameters associated with environmental impacts, while a few considered uncertainty in the environmental parameters.

2.2 Coping with uncertainty in SCM

A vast majority of the recent studies on supply chain problems are associated with various aspects of uncertainty (Choi et al., 2017), particularly focusing on the effects caused by environmental regulations (Allevi et al., 2018) and the carbon price (Rezaee et al., 2017). Some findings from these studies include different regulations, such as the carbon tax or the carbon trading systems, causing diverse effects on SCM. Rezaee et al. (2017) developed a two-stage stochastic programming model to design a green supply chain in a carbon trading environment in which the uncertainties in both the carbon price and product demand were incorporated. Han et al. (2017) addressed the potential regulations of carbon emissions restrictions in the problem of weight reduction technology selection and network design in a real-world corporation in China. A robust counterpart of the presented MILP model was used to address the uncertainty in a supply chain network resulting from weight reduction.

Although studies that integrate a consideration of uncertainty with green supply chain problems are still rare, a growing number of SCM studies have addressed the issue of uncertainty through various approaches. Different sources of uncertainty have been accounted for. In particular, designing a robust supply chain for facing uncertain demand has been widely explored. For example, Dong et al. (2005) considered multicriteria decision-making for both manufacturers and distributors, whereas the retailers are subject to decision-making under random demands for products. Gupta and Maranas (2003) proposed a bilevel framework in which the manufacturing decisions were modeled as ‘here-and-now’ decisions before the demand realization, and the logistics decisions were postponed in a ‘wait-and-see’ mode to optimize the decisions in the face of uncertainty. Some of the most recent studies took into consideration several uncertain factors simultaneously, such as both the supply disruption and demand variation. Ray and Jenamani (2016) proposed two models for optimal order allocation in a newsvendor setting, where both the supply and demand were uncertain. Furthermore, these studies developed a stochastic mathematical formulation for designing a network of multiproduct supply chains comprising several capacitated production facilities, distribution centers and retailers in markets under uncertainty. Baghalian et al. (2013) used a path-based formulation to consider supply-side uncertainties subject to possible disruptions in the manufacturers, distribution centers and their connecting links, in addition to accounting for an uncertain market. Other factors, such as volatile prices (Soleimani et al., 2016) or the uncertainty associated with production costs (Bidhandi and Yusuff, 2011), were analyzed when designing supply chain networks.

Insights and knowledge have been gained from these above-mentioned studies with regard to the effects of environmental concerns on SCM. Notably, not all the upstream and downstream sectors are exposed to a certain environmental regulation to the same degree; that is, the sectors characterized by carbon-intensive production processes are more vulnerable to carbon market uncertainties than those with fewer emissions. Nevertheless, in a supply chain where such sectors are interlinked, those that are not much affected by the carbon price variation will be exposed to the shocks caused by the more carbon price-sensitive sectors. This considerably influences the SCND. However, such mechanisms have not yet been sufficiently studied. Our study attempts to explore this question by establishing a supply chain model that incorporates the stochastic carbon price and conducting a real case study of PVC pipe manufacturing in China, in which the life cycle CO_2 emissions of the upstream PVC resin suppliers are significantly greater than those of the downstream pipe production.

3. Problem description

3.1 Supply chain network design

The networked supply chain in this study includes the suppliers of raw materials (PVC resin and other ingredients), plants for making different types of PVC pipes, warehouses for storing products and customers with given demands for those products (Fig. 1). There are multiple choices of transportation modes between the three stages, with various unit costs and emissions rates. The whole supply chain is subject to an uncertain carbon market. Five scenarios are set, corresponding with different ranges of the carbon price. The carbon price is assumed to be stochastic in each price range. The model supports the design and establishment of a supply chain that minimizes the total cost. The design includes the selection of suppliers, capacities of plants and warehouses, transportation modes, production amount and all the material flows across all the stages.

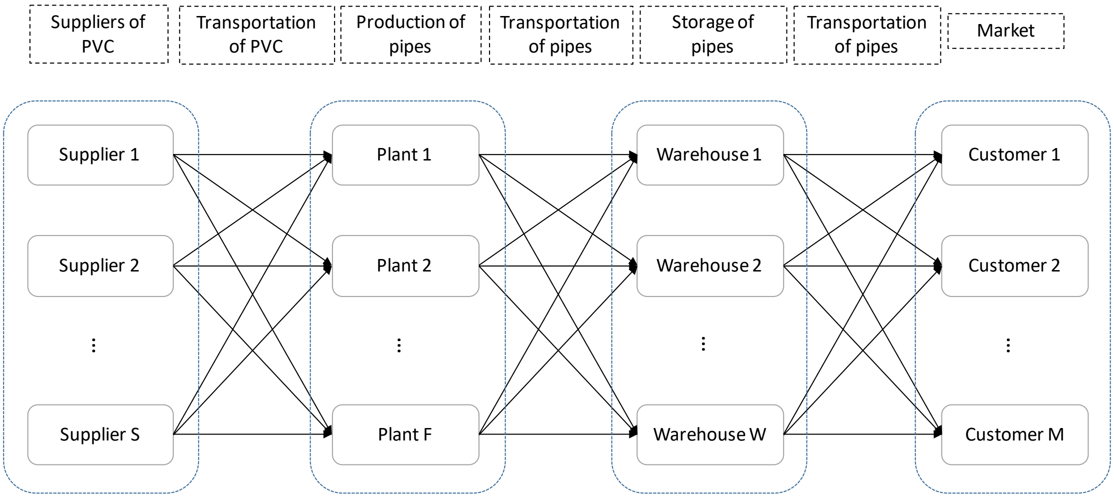

Fig. 1 Supply chain network for the PVC pipe sector.

Among all the stages, we take into account the CO_2 emissions in the production processes of the plants, the shipping processes with different modes and the embodied life cycle emissions for the raw material supply. As a result, the carbon price uncertainty impacts the purchase, production and transportation costs of PVC. Since the production processes of the raw materials are beyond the boundary of this conceived supply chain, a detailed life cycle analysis of its embodied emissions is necessary.

Chemical production, such as for PVC, features a long supply chain with diversified feedstocks, including coal, oil and natural gas, which include diverse economic costs, energy use, environmental impacts and carbon emissions. Typically, the energy usage determines the prevailing production cost components, which in turn implies that technologies with high energy demands can be phased out due to their low economic performance. Nevertheless, in certain cases, some interior technologies may outperform those energy efficient ones. For example, coal is much more abundant in China relative to oil and natural gas, which has led to lower coal prices for many years. Moreover, the relatively low capital requirements for some coal-based chemical plants on a small scale increase the competitive edge to some extent. These are the historical reasons for the existence of many coal-based technologies, particularly in China's chemical industry. A growing concern is caused by the specter of a nation-wide carbon market that results in adding considerable costs to the current production processes, which may result in a fundamental change in technology adoption in this industry. However, such a change largely depends on the carbon price signal, which in turn will depend on the gradually more stringent allowances issued by the government. Consequently, such a change will lead to either the refurbishment of the existing production lines with carbon mitigating technologies or to the phasing out of the existing production lines. Both measures will reduce the carbon footprint per unit-product, and this effect will pass through the supply chain within the whole economic system. Thus, even the sectors not directly exposed to the carbon price uncertainty (for instance, sectors with minor shares of carbon emission costs relative to the total production costs) may be affected in an indirect way, for instance, through the procurement of carbon-intensive goods.

3.2 Life cycle emissions of raw materials

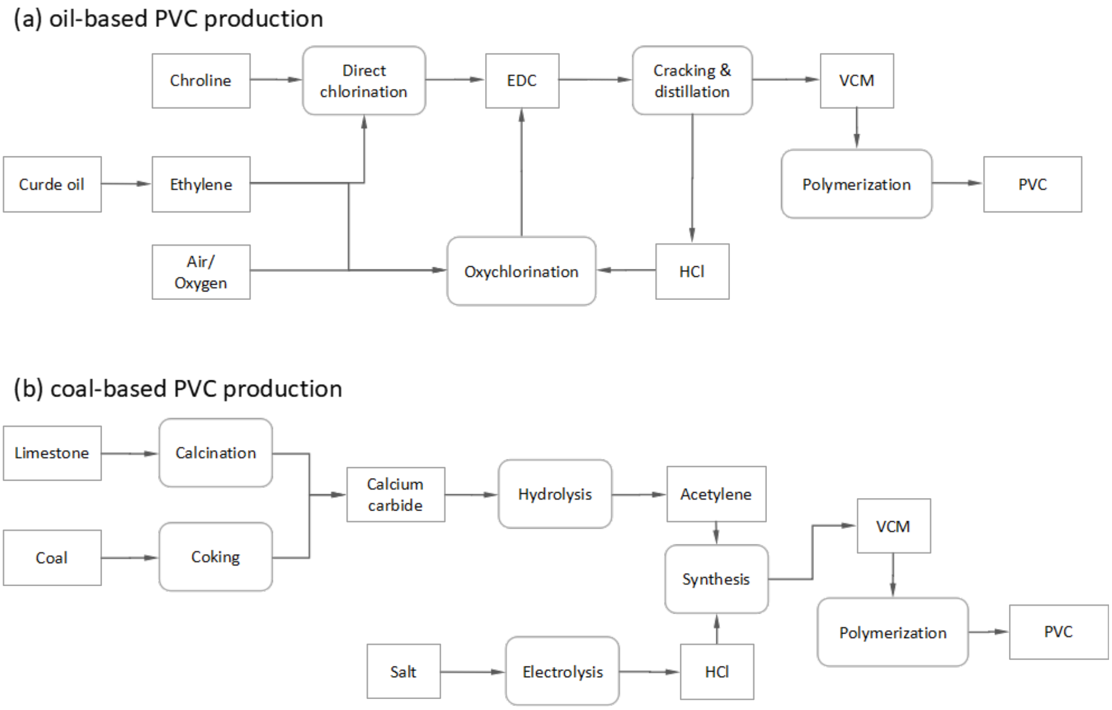

Fig. 2 Simplified processes of two PVC production approaches.

PVC can be produced from three typical fossil fuels, namely, coal, crude oil and natural gas. In China, the oil-based and coal-based approaches are mostly used due to the scarcity of domestic natural gas. These two fuels are characterized by the corresponding simplified process flows, shown in Panels (a) and (b) in Fig. 2. Oil-based PVC production employs ethylene, one of the most important petro-chemicals derived from crude oil, which reacts with chlorine during the direct chlorination step to generate 1,2-dichloroethane (EDC). The EDC is then fed to the cracking and distillation operations to yield vinyl chloride monomer (VCM), which is subsequently polymerized to PVC. The coal-based approach, however, follows a completely different process for the production of VCM, except for the last polymerization step. This method blends coke and lime, which are derived from coal coking and limestone calcination, respectively, in an electric arc furnace (EAF) where calcium carbide is formed. Calcium carbide is reacted with water to produce acetylene, which is then mixed with chlorine hydride (HCl) to synthesize the VCM. This coal-derived process is highly carbon intensive because some of the key steps, such as limestone calcination and coal coking, as well as the calcium carbide reaction in the EAF, require large amounts of energy (Liu et al., 2011). This process is also one of the highest CO_2-emitting industrial sectors (Zhu et al., 2010).

These two approaches are significantly different in terms of the energy consumption and the associated CO_2 emissions. We compiled data from different sources (European Climate Foundation, 2014; China Chemical Industry Information Center, 2016; Liu et al., 2011; Shang et al., 2011; Zhu et al., 2010) to assess the life cycle CO_2 emissions per unit of PVC production from these two typical approaches, as shown in Table 1. The results show that the life cycle emissions of the coal-based PVC are approximately 7.66 tons/ton PVC, more than three times those from the oil-based route, which are 2.25 tons/ton PVC. This significant disparity stems from the feedstock preparation, that is, the calcium carbide production from coal consumes a considerably larger amount of energy than that of oil-derived ethylene.

Table 1 Life cycle CO2 emissions for PVC production through two approaches.

Technology			Unit consumption	CO_2 emissions coefficient	CO_2 emissions per unit PVC
			tons/ton PVC	tons/ton	tons/ton PVC
Oil-based process	Feedstock	Ethylene	0.31	2.38	0.74
		Chlorine	0.75	1.82	1.37
	Production				0.15
	Total				**2.25**
Coal-based process	Feedstock	Calcium carbide	1.45	4.11	5.96
		Chlorine hydride	0.75	2.07	1.55
	Production				0.15
	Total				**7.66**

Note that the CO_2 emissions coefficient we calculate for calcium carbide is lower than what was reported in a previous study in 2011 (Liu et al., 2011); this result is because, over the past decade, the industry has achieved some improvements in energy efficiency by adopting advanced technologies, phasing out small-scale and interior capacities, etc.

4. Model specification

The model supports the analysis of the impacts of the uncertain carbon prices on the total supply chain network cost minimization, which implies the corresponding optimal design of the supply chain, in particular the number of facilities at each echelon of the chain, the transportation mode selection, and the quantities of the material flows between the network facilities. The general form of the mixed-integer linear programming model can be stated as follows:

$$\min z = c^T x \tag{1}$$

$$\begin{aligned} subject\ to: Ax = b \\ d_l \le x \le d_u \end{aligned} \tag{2}$$

where x denotes the variables, c is the vector of the cost coefficients, A is the matrix of the coefficients in the constraints, b is the right-hand side column vector of the constraints, and d_l and d_u are the vectors of the lower and upper bounds on the variables, respectively. The objective function value, z, in Eq. (3) represents the overall SCND costs consisting of the cost items associated with each echelon of the chain, including the procurement costs (PC), manufacturing and storage costs (MC) and transportation costs (TC).

$$z = PC + MC + TC \tag{3}$$

The complete specification of the implemented model is summarized below.

Indices

s Index of suppliers, $s = 1, ..., S$

r Index of raw materials, $r = 1, ..., R$

f Index of manufacturing plants, $f = 1, ..., F$

p Index of products, $p = 1, ..., P$

w Index of warehouses, $w = 1, ..., W$

t Index of transportation modes, $t = 1, ..., T$

n Index of customers, $n = 1, ..., N$

Parameters

cps_{rs} Capacity of raw material r provided by supplier s

slc_s Selection costs of supplier s

ems_{rs} Life cycle CO_2 emissions per unit of raw material r provided by supplier s

prs_{rs} Price per unit of raw material *r* provided by supplier *s*

cr_{rp} Conversion rate of raw material *r* to product *p*

cpf_{pf} Capacity of product *p* produced by plant *f*

ccf_{f} Capital costs of establishing plant *f*

acf_{f} Annualized capital costs of establishing plant *f*

vcf_{p} Variable costs of producing one unit of product *p*

emp_{p} CO_2 emissions for producing one unit of product *p*

cpw_{pw} Storage capacity of product *p* in warehouse *w*

ccw_{w} Capital costs of establishing warehouse *w*

acw_{w} Annualized capital costs of establishing warehouse *w*

ccw_{w} Capital costs of establishing warehouse *w*

tcs_{sft} Unit transportation costs for shipping a unit of raw material from supplier *s* to plant *f* through mode *t*

dts_{tsf} Distance from supplier *s* to plant *f* through mode *t*

tcf_{tfw} Unit transportation costs for shipping a unit of product from plant *f* to warehouse *w* through mode *t*

dtf_{tfw} Distance from plant *f* to warehouse *w* through mode *t*

tcw_{twn} Unit transportation costs for shipping a unit of product from warehouse *w* to customer *n* through mode *t*

dtw_{twn} Distance from warehouse *w* to customer *n* through mode *t*

emt_{t} Unit CO_2 emissions for shipping through mode *t*

dm_{pn} Demand for product *p* from customer *n*

cp Market price per unit of CO_2 emissions allowance

Decision variables

AS_{rsf} Amount of raw material *r* provided by supplier *s* to plant *f*

TS_{rtsf} Amount of product *p* transported from supplier *s* to plant *f* by mode *t*

AF_{pf} Amount of product *p* produced by plant *f*

TF_{ptfw} Amount of product *p* transported from plant *f* to warehouse *w* through transportation mode *t*

TW_{ptwn} Amount of product *p* transported from warehouse *w* to customer *n* through transportation mode *t*

$$SI_s = \begin{cases} 1, & \text{If supplier } s \text{ is selected} \\ 0, & \text{Otherwise} \end{cases}$$

$$SF_f = \begin{cases} 1, & \text{If plant } f \text{ is established} \\ 0, & \text{Otherwise} \end{cases}$$

$$SW_w = \begin{cases} 1, & \text{If warehouse } w \text{ is established} \\ 0, & \text{Otherwise} \end{cases}$$

The three sets of decision variables (*SI*, *SF*, and *SW*) are binary, while all the other model variables take real values. All the relationship constraints are linear with respect to the model variables. The carbon price, *cp*, is assumed to follow a uniform distribution. The mean values of the outcome variable distributions are taken for the analysis. Therefore, from the mathematical programming perspective, the model is a stochastic MILP (Mixed-Integer Linear Programing) formulation. The model has 230 variables (including 9 binary variables) and 70 constraints. We assume the uniform distribution of the carbon price within the corresponding range. In addition to the decision variables presented above, the model includes auxiliary variables to define various quantities that are helpful in the model specification and analysis. These variables are presented below along with the corresponding relationships.

The objective of the model is to find the optimal solution that minimizes the total cost presented symbolically by Eq. (3). The cost components, each defined by the corresponding auxiliary variables, are as follows. The procurement costs, defined by Eq. (4), consist of the purchasing costs of the raw materials, the costs for the CO_2

emissions embodied in the raw material supply[1] and the costs for supplier section.

$$PC = \sum_{r\in R}\sum_{s\in S}\sum_{f\in F} prs_{rs}\cdot AS_{rsf} + cp\cdot\sum_{r\in R}\sum_{s\in S}\sum_{f\in F} AS_{rsf} + \sum_{s\in S} slc_s\cdot SI_s \tag{4}$$

The manufacturing and storage costs measure all the items associated with the manufacturing and storage processes, which include the annualized capital costs of plants and warehouses, the variable production costs, and the costs for CO_2 emissions during the production process, as shown in Eq. (5).

$$MC = \sum_{f\in F} acf_f\cdot SF_f + \sum_{p\in P}\sum_{f\in F} vcf_p\cdot AF_{pf} + cp\cdot\sum_{p\in P}\sum_{f\in F} emp_p\cdot AF_{pf} + \sum_{w} acw_w\cdot SW_w \tag{5}$$

The transportation costs represent all the transportation costs from suppliers to plants, from plants to warehouses, and from warehouses to customers, as well as the costs of the CO_2 emissions associated with the transportation and the selection costs of the suppliers, as shown in Eq. (6).

$$\begin{aligned} TC = {} & \sum_{r\in R}\sum_{t\in T}\sum_{s\in S}\sum_{f\in F} dts_{tsf}\cdot tcs_{tsf}\cdot TS_{rtsf} + cp\cdot\sum_{r\in R}\sum_{t\in T}\sum_{s\in S}\sum_{f\in F} emt_t\cdot dts_{tsf}\cdot TS_{rtsf} \\ & + \sum_{p\in P}\sum_{t\in T}\sum_{f\in F}\sum_{w\in W} tcf_{tfw}\cdot dtf_{tfw}\cdot TF_{ptfw} + cp\cdot\sum_{p\in P}\sum_{t\in T}\sum_{f\in F}\sum_{w\in W} emt_t\cdot dtf_{tfw}\cdot TF_{ptfw} \\ & + \sum_{p\in P}\sum_{t\in T}\sum_{w\in W}\sum_{n\in N} tcw_{twn}\cdot dtw_{twn}\cdot TW_{ptwn} + cp\cdot\sum_{p\in P}\sum_{t\in T}\sum_{w\in W}\sum_{n\in N} emt_t\cdot dtw_{twn}\cdot TW_{ptwn} \end{aligned} \tag{6}$$

Model constraints

The model solution must conform to the constraints explained as follows. Constraints (7) - (9) represent the capacity constraints. Constraint (7) ensures that the amount of each raw material, *r,* provided by each supplier, *s,* should not exceed the corresponding capacity. Constraint (8) ensures that for every plant, *f*, the total amount of product, *p,* it produces should be within its capacity for this product. Constraint (9) enforces the warehouse storage limitation that the amount of all the products sent to warehouse *w* should not be larger than its capacity.

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[1] For certain goods, the costs of the CO_2 emissions in the production process are already incorporated in the market price. However, to better illustrate the effects from carbon market uncertainty, we separate this part out of the goods price. Hence, the parameter of the raw material price, *prs,* is essentially the net price or the carbon-free price without the CO_2 emissions costs. Moreover, the costs calculated for life-cycle emissions ensure that the impacts from all the upstream sectors beyond the boundary of the proposed supply chain have been accounted for.

$$\sum_{f\in F} AS_{rsf} \le cps_{rs} \quad \forall\, r\in R, s\in S \tag{7}$$

$$\sum_{p\in P} AF_{pf} \le cpf_f \cdot SF_f \quad \forall\, f\in F \tag{8}$$

$$\sum_{p\in P}\sum_{t\in T}\sum_{f\in F} TF_{ptfw} \le cpw_w \cdot SW_w \quad \forall\, w\in W \tag{9}$$

The material flow equilibrium equations are represented by constraints (10) - (15). Constraint (10) shows that the amount of each raw material *r* from supplier *s* to plant *f* equals the total amount of this raw material *r* transported by all the modes between the same nodes. Constraint (11) represents the mass balance relationship between the raw material input fed into the manufacturing process and the output from it. Constraint (12) ensures that the output of product *p* from plant *f* equals the total amount of this product from the same plant to all the warehouses through all the transportation modes. Constraint (13) formulates the inflow and outflow balance of each product in each warehouse. Constraint (14) enforces that the outflow of product *p* from warehouse *w* to customer *n* meets the demand for this product from customer *n*. Constraint (15) guarantees that the total production of product *p* from all the plants should meet the total demand for it from all the customers.

$$AS_{rsf} = \sum_{t\in T} TS_{rtsf} \quad \forall\, r\in R, s\in S, f\in F \tag{10}$$

$$cr_{rp} \cdot \sum_{s\in S} AS_{rsf} = \sum_{p\in P} AF_{pf} \quad \forall\, r\in R, f\in F \tag{11}$$

$$AF_{pf} = \sum_{t\in T}\sum_{w\in W} TF_{ptfw} \quad \forall\, p\in P, f\in F \tag{12}$$

$$\sum_{t\in T}\sum_{f\in F} TF_{ptfw} = \sum_{t\in T}\sum_{n\in N} TW_{ptwn} \quad \forall\, p\in P, w\in W \tag{13}$$

$$\sum_{t\in T}\sum_{w\in W} TW_{ptwn} = dm_{pn} \quad \forall\, p\in P, n\in N \tag{14}$$

$$\sum_{f\in F} AF_{pf} = \sum_{n\in N} dm_{pn} \quad \forall\, p\in P \tag{15}$$

5. Case study: results and analysis

5.1 Case study background

A selected PVC pipe manufacturing company in China is used as the case study. The company utilizes PVC resin and other ingredients to produce different types of PVC pipes, which are commonly used in building and construction for drainage, waste and ventilation applications. The manufacturing process includes several main stages, such as extrusion and molding, where the feedstock can be transformed into the finished plastic products. The company purchases the PVC resin and other ingredients from different suppliers. The PVC resin may be produced either by oil-based or coal-based technology. Typically, the oil-based PVC has better quality; thus, the price is slightly higher, while its embodied CO_2 emissions are also much lower than those of the coal-based technology. We consider one supplier of the oil-based PVC, two suppliers of the coal-based PVC, and one supplier of other ingredients. The company is considering establishing plants and warehouses with enough capacity to enable the fulfillment of the given demands for the different types of PVC pipes from three customers. The raw materials and products can be transported by trucks or trains or can be shipped with different costs and CO_2 emission intensities. In addition, the distances between the upstream and downstream facilities are different across these modes. Table 2 lists the numbers of suppliers, plants, product types, warehouses, customers, and transportation modes in this case study.

Table 2 Numbers of facilities in each echelon of the supply chain.

Stage	Number of facilities	Description
Supplier	4	Supplier A, oil-based PVC; Supplier B and C, coal-based PVC; and Supplier D, ingredients
Plant	3	Plant A, B and C with different capacities of products
Product type	3	P50, product with the size of 50.0 mm*2.0 mm; P75, product with the size of 75.0 mm*2.2 mm; and P110, product with the size of 110.0 mm*3.2 mm
Warehouse	2	Warehouse A and B with different capacities of storage
Customer	3	Customer A, B and C with different demands for each product type
Transportation mode	3	Three transportation modes include truck, train and ship.

China's carbon trading market started in 2011. In the early stage, seven pilot markets were established in Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong and Shenzhen. At the end of 2017, China launched its nationwide carbon market, which is also the largest carbon trading market in the world. Although not all the industrial sectors are currently covered by the market, the market is planned to include more sectors, particularly those with high CO_2 emissions. The coal chemical industry is one of the most carbon-intensive sectors. The coal-based PVC dominates China's PVC production, unlike more industrialized economies where the oil-based or natural gas-based routes take up almost the whole market. The development of the carbon market and increasingly stringent environmental policies will impose significant risks on China's coal chemical industry, as well as the downstream sectors. The carbon price in this case study is considered to be stochastic. The historical prices of the carbon traded in the pilot markets show that the price varied over a wide range, mostly between 10-40 yuan/ton (De Boer et al., 2017). In some extreme cases, the price even decreased below 10 yuan/ton. However, the Beijing market has always observed a relatively higher price of above 50 yuan/ton. Given the growing demand for emission allowances, it is widely expected that the price will increase to 100 yuan/ton before 2025 (De Boer et al., 2017).

5.2 Data collection and assumptions

We collected all the data required for defining the model parameters. Table 3 presents the key parameters for the suppliers. Typically, the oil-based PVC production has a relatively larger scale than the coal-based PVC and features higher product quality. Thus, the oil-based PVC resin also has a higher market price than that of the coal-based PVC. Table 4 shows the capacities, establishment costs and variable costs for the plants and the warehouses. There are economies of scale that are indicated by the relationship between the establishment cost and plant capacity. For example, Plant A is the largest plant and thus has the lowest establishment cost per unit of capacity. The unit costs and emissions intensity for different transportation modes are summarized in Table 5. Among the three modes, railway has the lowest cost and CO_2 emissions. In contrast, road transport is the most expensive and CO_2 intensive mode. The ship transport cost is between the other two. Table 6 presents the demands of the three customers for each product type.

Table 3 Key parameters for suppliers.

Supplier type	Capacity (ton/yr)		Price (yuan/ton)
Supplier A	150,000	PVC resin (oil route)	6,750
Supplier B	90,000	PVC resin (coal route)	6,350
Supplier C	60,000	Ingredients	17,000
Supplier D	2,000		

Table 4 Key parameters for plants and warehouses.

Facility	Capacity (ton/yr)	Establishment cost (yuan)
Plant A	85,000	255,000,000
Plant B	75,000	240,000,000
Plant C	65,000	225,000,000

Warehouse A	60,000	42,000,000
Warehouse B	80,000	48,000,000
Product type	Variable cost (yuan/ton)	
P50	510	
P75	470	
P110	415	

Table 5 Unit cost and CO_2 emissions of the three transportation modes.

Transportation mode	Unit cost (yuan/ton*km)	Unit emissions (kg/ton*km)
Road	0.53	0.07
Railway	0.15	0.025
Ship	0.17	0.043

Table 6 Demands of the three customers for different types of products.

Customer type	P50 (ton/yr)	P75 (ton/yr)	P110 (ton/yr)
Customer A	9,886	24,551	10,065
Customer B	15,790	15,346	6,056
Customer C	10,588	19,948	8,060

Considering both the historical price variations in the seven pilot carbon markets and the price projection for the near-term future (De Boer et al., 2017), we examined five scenarios of carbon price variation ranges, namely, 0-25, 25-50, 50-75, 75-100, and 100-120 yuan/ton (denoted as Scenarios I to V, respectively, shown in Table 7). For each scenario, we assume a uniform distribution of the carbon price within the corresponding range and take the mean values of the outcome variable distributions.

Table 7 Assumptions of the five carbon price scenarios.

Scenario	Carbon price range (yuan/ton)
Scenario I	0-25
Scenario II	25-50
Scenario III	50-75
Scenario IV	75-100
Scenario V	100-125

5.3 Results and discussion

5.3.1 Impacts on supply chain configuration

The numerical results show the significant impacts of the carbon price uncertainty on the supply chain configuration. The different configurations for each of the five designed scenarios are presented in Figs. 3 to 7. In these figures, the arrows with numbers show the directions and amounts of the material flows. In Fig. 3, for example, Supplier B provides Plant A with 89,764 tons and Plant C with 526 tons of coal-based PVC as feedstock, while Supplier C provides 36,621 tons of coal-based PVC to Plant C. The different types of products from these two manufacturers are stored at different stockpile levels in Warehouses A and B, which deliver the products to the three customers according to their respective demands. Likewise, Figs. 4 to 7 show the configurations across the other four scenarios. The most conspicuous change is the selection of the suppliers. In the scenarios with lower carbon prices, the manufacturers prefer to purchase coal-based PVC (Figs. 3 and 4), while in the scenarios with higher carbon prices they opt for oil-based PVC (Fig. 5-7), as the increased carbon price inevitably adds extra cost to the coal-based PVC, which is far more carbon-intensive. The price range triggering this change in supplier selection is 50-75 yuan/ton. In the manufacturing stage, Plant A always reaches its maximum capacity, since it has the largest capacity and thus the lowest capital costs per unit of capacity. Both the warehouses are built close to the customers. The transportation mode is selected and influenced by the distance, unit costs and additional costs from the CO_2 emissions.

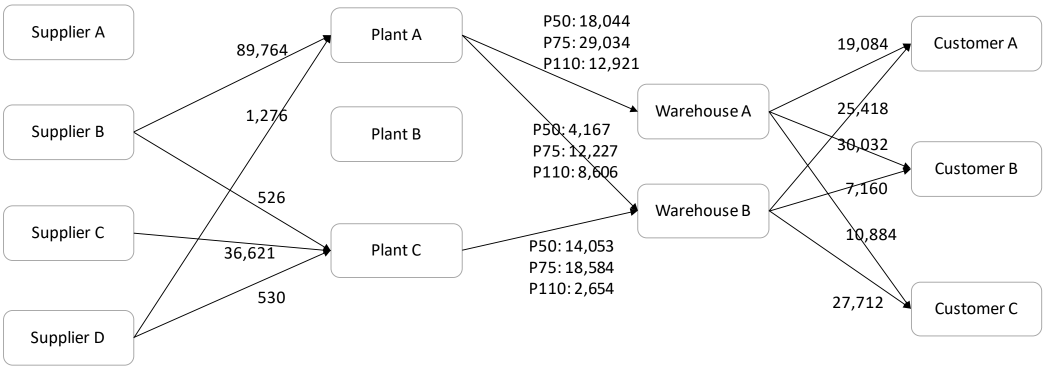

Fig. 3 Supply chain configuration for Scenario I.

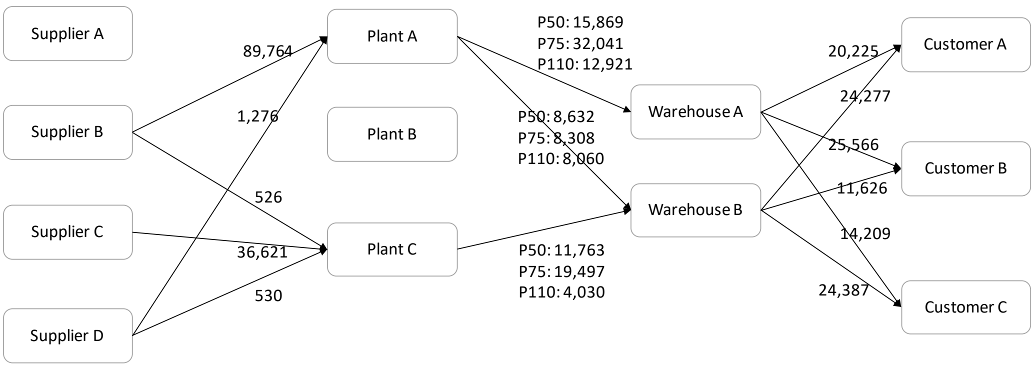

Fig. 4 Supply chain configuration for Scenario II.

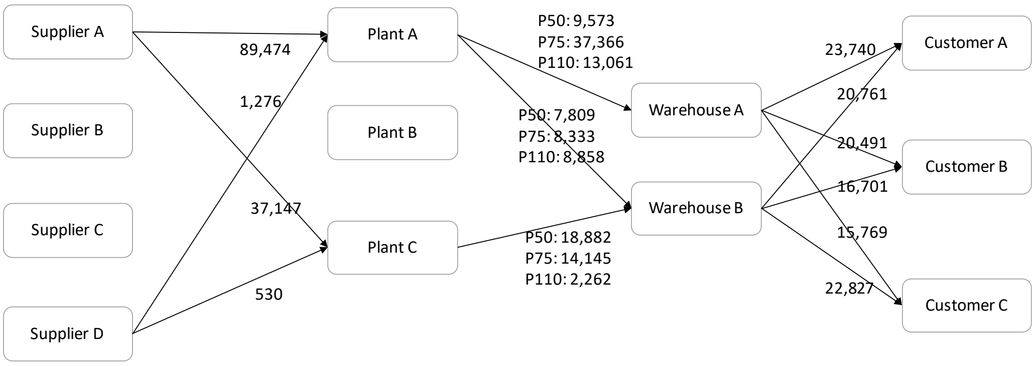

Fig. 5 Supply chain configuration for Scenario III.

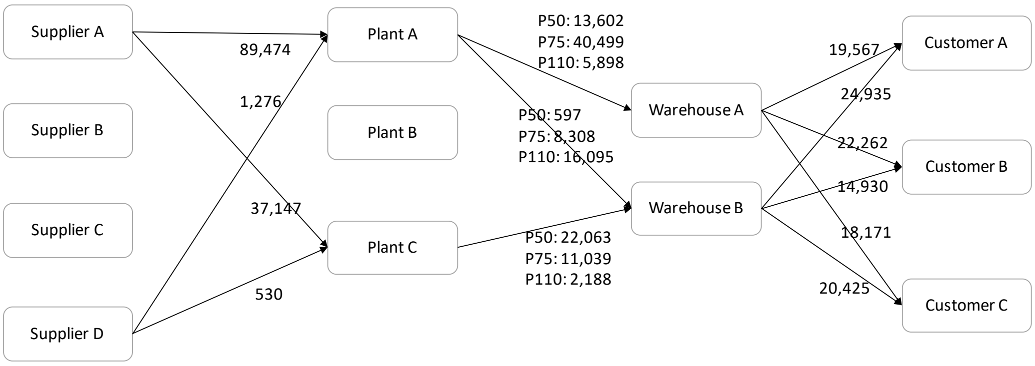

Fig. 6 Supply chain configuration for Scenario IV.

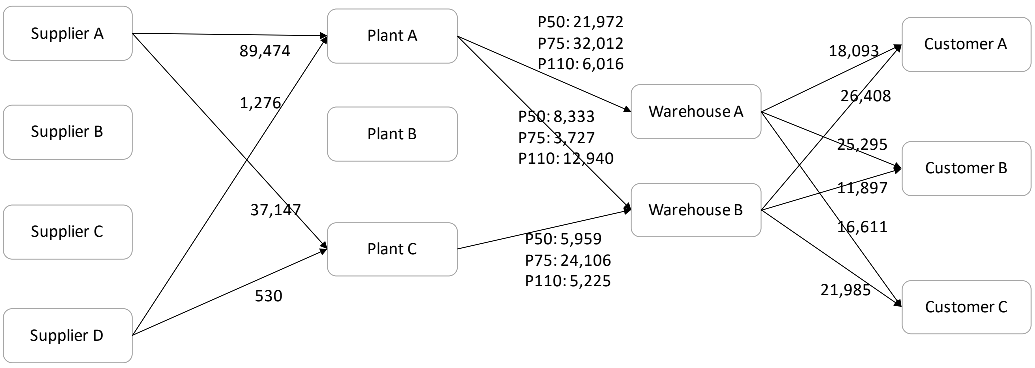

Fig. 7 Supply chain configuration for Scenario V.

The variation of the carbon price has obvious effects on the supply chain costs. As Table 8 shows, the total costs increase from 1,007 to 1,065 million yuan, or by 5.8% in terms of the highest carbon price scenario compared to the lowest one. The breakdown of the cost items shows more diversified changes. The procurement costs increase along with the higher carbon price, as do the manufacturing costs. The transportation costs, however, decrease from Scenario III to Scenario II, mainly because the supplier has been shifted to the oil-based route, which has a relatively short distance between the suppliers and plants.

Table 8 summary of supply chain configurations for different carbon price scenarios.

Carbon price scenario (yuan/ton)	Procurement cost (yuan)	Manufacturing and storage cost (yuan)	Transportation cost (yuan)	Total cost (yuan)
Scenario I: 0-25	871,836,927	98,426,449	37,473,948	1,007,737,324
Scenario II: 25-50	896,242,897	99,097,106	37,660,783	1,033,000,786
Scenario III: 50-75	914,862,124	99,767,763	33,992,785	1,048,622,672
Scenario IV: 75-100	922,142,597	100,438,421	34,157,461	1,056,738,478
Scenario V: 100-125	929,423,069	101,109,078	34,322,137	1,064,854,284

5.3.2 Impacts on CO_2 emissions

The CO_2 emissions from the entire supply chain are significantly influenced by the carbon price, as shown in Fig. 8. Note that we use the life cycle emissions here. Again, the abrupt drop in emissions across the scenarios occurs when suppliers are changed, which divides the scenarios into two groups. The first group consists of the higher emission scenarios with a low carbon price (Scenarios I and II), and the second group has lower emissions enforced by the higher carbon price. The emissions from the procurement stage in the first group are approximately 30% of those in the second group, thus implying substantial reduction potential from the change of suppliers.

In either case, the emissions from the procurement stage dominate the total emissions, thus indicating that the feedstock production is the main emissions source in the whole supply chain of PVC pipes. This result implies that the technological advancement in the upstream sectors provides significant emission reductions in the whole chain. The emissions from the manufacturing stage are kept the same across all the scenarios since the production scale remains the same to meet the demand. The transportation emissions, accounting for the smallest proportion, decline by approximately 12% in the higher carbon price scenarios.

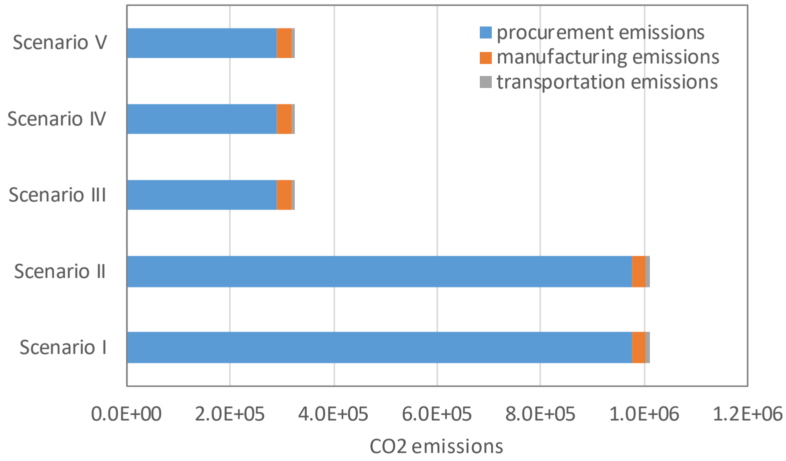

Fig. 8 Life cycle CO_2 emissions of the five scenarios.

Fig. 9 illustrates the dual effects of CO_2 emissions and the costs associated with the increased carbon price within the different stages of the supply chain. The shifting patterns vary significantly among these stages. In the procurement stage, the emissions remain the same in the first two scenarios, while the costs increase. Scenario III shows a deep drop in both the emissions and costs, resulting from the changes in suppliers. In the other two scenarios, the emissions remain at the same level, but the costs increase due to the higher carbon price. Even when the price reaches 100-125 yuan/ton, as represented by Scenario V, the associated costs are still lower than those of Scenario II, in which the coal-based PVC suppliers are selected. The manufacturing and storage stage shows a stable level of emissions across the scenarios; hence, the costs increase along with the carbon price. The emissions from the transportation stage drop moderately from Scenario III, thus leading to a minor increase in the associated cost from Scenario II. Since the total emissions in the whole chain are dominated by procurement, the pattern for the total emissions and costs is very similar to that in the procurement stage.

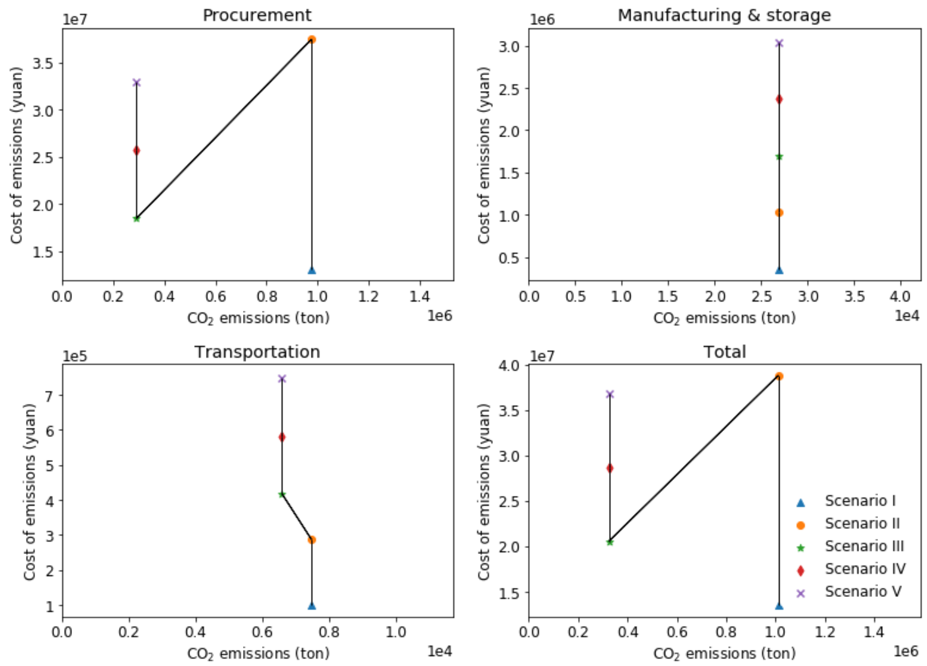

Fig. 9 Relations between costs of emissions and CO_2 emissions across the five scenarios for different stages.

6. Conclusion and discussion

Concerns about climate change and environmental issues increasingly affect decision-making in the supply chain design and management processes. Emissions trading systems, having been proven to be an effective tool in environmental regulation, have been widely adopted by many countries. This kind of market mechanism (similar to various environmental exchange markets) can facilitate the control of total emissions in a certain region and provide flexibility for the entities within it to select their best strategies according to the price signals. The carbon price uncertainties cause substantial risks for supply chains. Although the manufacturing processes may be relatively less carbon-intensive within the whole chain, they can also be greatly exposed to such uncertainties because of the high life cycle emissions in the feedstock procurement processes. To understand how these embodied effects work, this study constructs a supply chain decision-making model and uses the case of PVC pipe production in China. Two alternative PVC production strategies, namely, oil-based and coal-based technology, with distinct life cycle CO_2 emissions, are considered. Five scenarios of the carbon price ranging from 0-125 yuan/ton are designed, which assume a stochastic price variation.

The results from our model demonstrate both the direct and indirect effects of the carbon market fluctuations on the supply chain design and management via various mechanisms. A carbon price level of over 50-75 yuan/ton drives the selection of suppliers in favor of the oil-based production. The total costs of the whole chain increase by 5.8% in the scenario with the highest carbon price compared to the one with the lowest price, while the total CO_2 emissions decrease by 70%. Among all the stages, procurement plays a predominate role in terms of the total emissions and the associated costs, which eclipses the influences from other stages. Given that the "triggering price level" calculated in this study is not high, the downstream manufacturing of the PVC products is subject to substantial risk conveyed from the upstream sectors. The distinctive feature of the supply chain designed in our study lies in the relatively low carbon intensities within the manufacturing, storage and transportation stages compared to the life cycle emissions embodied in the procurement processes. Uncertainty from the carbon market affects the operation of the supply chain in all the stages.

Our study suggests that a gradual and smooth introduction of a carbon market can minimize the impacts on the entire manufacturing industry. As the alteration of the upstream production towards advanced low-carbon technologies is driven by the procurement of the downstream sectors through the carbon price signal, abrupt price jumps may lead to significant consequences for the low-carbon transitions of industrial sectors. In contrast, if the carbon price remains at a low level, it would not provide a sufficient driving force for such a transition. Examples of the currently operating carbon markets include the European Union Emissions Trading System (EU ETS) and the Regional Greenhouse Gas Initiative (RGGI). Some experiences and lessons in pricing mechanisms can be learned from these markets for designing China's nation-wide carbon trading scheme. In the globalization era, manufacturing sectors are gradually exposed to a wide range of outsourcing risks. From the supply chain perspective, secure and responsible consumption requires the diversification of not only the domestic production but also the imports (Kharrazi et al., 2015).

The stochastic mixed integer linear programming model developed in this study demonstrates its effectiveness in evaluating the carbon price uncertainty impacts on the downstream manufacturing sectors. Nevertheless, the presented modeling approach has some limitations. Typically, a higher carbon price predominantly affects the production and transportation operations, thus resulting in the corresponding changes in the supply chain configurations towards low-carbon production technologies and reduced transportation costs, although not necessarily with linear relationships. Some sources of uncertainty, such as the fuel price fluctuation and demand variation, are not taken into account in this study. The market costs of the different PVC routes largely depend on the relative changes of the coal and oil prices, which would add much more complexity to the analysis. In addition, the analysis of the outsourcing risks in the global trade context is not included in this study. Other decision-making modeling approaches show advantages in some aspects, e.g., the real options modeling approach that incorporates the price uncertainty in assessing the investment flexibility (Zhou et al., 2014) and multiperiod supply chain planning models that can be developed by multistage stochastic programming (Rezaee et al., 2017). An input-output analysis and network flow analysis also provide effective tools for assessing the resilience of a supply chain in a global trade context (Kharrazi et al., 2017). Various combinations of such modeling approaches can motivate diverse future research in this area. Moreover, a wider range of feedstock production technologies can also be included, such as natural gas or biomass-based PVC production. These low carbon sources can lead to substantial changes in the supply chain performance when facing uncertain carbon prices. All these considerations suggest the need for future work in this area.

Acknowledgements

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